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Short Communication

Predation on endangered mussels by invasive raccoons: a case study from western Poland

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Abstract

The raccoon *Procyon lotor* is an invasive alien carnivorous mammal whose impact on populations of native species in Europe is poorly understood. Raccoon populations are rising both in range and density, which increases predation pressure. The raccoon is a food opportunist and its impact on local animal populations depends on the availability of food, especially during the critical winter period. In the winter of 2020–2021, we observed an extreme accumulation of empty shells of native mussels (Bivalvia, Unionidae) foraged by raccoons in the Lubuskie Lakeland in western Poland. The aim of this study was to determine whether mussels could be an important food source for raccoons during the difficult winter period in areas where they have been introduced. We hypothesised that raccoons would prefer thin-shelled mussels over thick-shelled species as their food. We identified the mussel species and estimated their numbers in the piles of shells found on the small river banks. The raccoons' prey consisted of 2,340 mussels belonging to three genera (*Anodonta*, *Pseudanodonta*, *Unio*) and five species (*Anodonta cygnea*, *Anodonta anatina*, *Unio pictorum*, *Unio tumidus*, *Pseudanodonta complanata*). Two of them, the *Anodonta cygnea* and *Pseudanodonta complanata*, have the status of endangered species in Poland and are red listed by IUCN respectively as Vulnerable (VU) in Europe and Endangered (EN) globally.

Key words: Bivalvia, foraging, invasive alien species, Poland, *Procyon lotor*

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Introduction

Invasive alien species are a global problem for nature conservation and affect native species in colonised areas in many ways, including through predation. They can become a new, non-native factor affecting local species populations, or they can expand the guild of existing predators and increase pressure on potential prey (e.g. Parker et al. 1999; Blackburn et al. 2004; Vilà et al. 2010; Keller et al. 2011; O'Donnell et al. 2015; Bellard et al. 2016; Doherty et al. 2016; Mollot et al. 2017; Osaki et al. 2019).

The raccoon is a food opportunist whose diet varies geographically. However, its diet is similar in similar habitats (Lotze and Anderson 1979; Rulison et al. 2012). It consumes large amounts of plant food, including maize

and fruit (Costa 1951). However, in its natural range, the raccoon preys on many animal species e.g. birds (Hartman et al. 1997; Hartman and Eastman 1998; Schmidt 2003; Ellis et al. 2007), freshwater, marine and coastal turtles (Feinberg and Burke 2003; Engeman et al. 2005; Burke et al. 2009; Karson et al. 2018), crustaceans (Waldstein Parsons et al. 2013) and invasive snails (Carter et al. 2017). In the areas where it has been introduced, it also preys on many reptile, bird and mammal species (e.g. Ikeda et al. 2004; Bartoszewicz et al. 2008; García et al. 2012; Michler 2017).

The raccoon has joined a large guild of mesopredators and competes with them to a greater or lesser extent for food resources. However, our knowledge of the threat posed by raccoons to native European species is incomplete (Salgado 2018). In Germany, raccoons have been observed to be more active than other predators in protected waterbird breeding areas (Fiderer et al. 2019). In Poland, raccoons were found to increase the mortality of hibernating bats in the one of the largest hibernation sites (Cichocki et al. 2021). In Italy, raccoons have been reported to prey on the endangered white-clawed crayfish *Austropotamobius pallipes* complex (Boncompagni et al. 2021; Tricarico et al. 2021).

In the public consciousness and in the media, the common message is that raccoons have no negative impact on the ecosystem. The food opportunism of this species makes it difficult to determine their impact on the different species of their prey (e.g. Bartoszewicz et al. 2008; Rulison et al. 2012). Classical methods of analysing a predator's diet, based on microscopic analysis of identifiable remains in scats, are not sufficient to estimate the extent of exploitation of individual food sources. For some prey groups, e.g. birds and turtles, direct observations of nest sites can provide valuable data on the extent of raccoon predation (e.g. Ellis et al. 2007; Karson et al. 2018). One group of prey whose traces are rarely found in raccoon scats are mussels (Michler 2017).

More than 2,000 predator species forage on mussels (Meira et al. 2024). Mussels are in the diet of many terrestrial carnivorous and omnivorous mammal species. In freshwater ecosystems in Poland, they have so far been found in the diet of the native otter *Lutra lutra* (Krawczyk et al. 2011; Zając 2014; Zalewska et al. 2020) as well as the introduced muskrat *Ondatra zibethicus* (Wołk 1979) and the raccoon (Bartoszewicz et al. 2008). The proportion of mussels in the diet of raccoons is believed to be generally low (Costa 1951; Smith et al. 1987; Tyler et al. 2000; Bartoszewicz et al. 2008; Engelmann et al. 2011; Rulison et al. 2012; Michler 2017). In some studies, this prey group was not detected in the diet of raccoons (Lotze and Anderson 1979; Feinberg and Burke 2003; Schmidt 2003; Azevedo et al. 2006; Ellis et al. 2007; Waldstein Parsons et al. 2013).

Some authors emphasise the important role of invasive predators that affect freshwater biodiversity (Meira et al. 2024). The aim of this study was to determine whether raccoons feed on mussels in areas where they have been introduced and whether these could be an important food source for raccoons during the difficult winter period. Mesocarnivores such as otters prefer to prey on thin-shelled mussels (Zając 2014). We hypothesised that thin-shelled bivalves are consumed more frequently by raccoons than thick-shelled species.

Material and methods

The study was conducted in a lowland landscape in western Poland in the Lubuskie Lakeland. This is an area where the raccoon has been constantly present for over 20 years (Gabryś et al. 2014). In winter 2020/21, on an approximately 100 m long section of the Paklica River channel connecting the Lubrza and Paklicko Wielkie lakes (52°18'59.9"N, 15°26'34.1"E, Fig. 1), we observed for the first time in many places an accumulation of mussels with feeding marks indicative of a raccoon, as well as the scats of this species in many places where mussels had accumulated (Fig. 2). The shape of the shell damage with the characteristic mapping of the tusks indicates that it could not have been caused by other mammal species, e.g. rodents. Furthermore, coypu *Myocastor coypus* and muskrat, which are the most probable rodent candidates for the bivalve predators, have not been observed in the study area. The muskrats have disappeared from large parts of Poland (Brzeziński et al. 2010). No otter tracks or scats were observed in the surveyed section of the watercourse. The water flow in the canal is always slow and the water level does not increase significantly even after heavy rainfall or snowmelt. There is a motorway overpass in the middle of the studied section of the watercourse. Near the overpass, the banks are paved with stones and further away the watercourse naturally becomes shallower. After a few dozen metres on either side of the overpass, reed beds that are difficult to access extend towards the two lakes. Therefore, this part of the deep channel was not sampled and was not considered a good habitat for the racoons foraging on mussels. Adjacent to the watercourse is a wooded area with black alder *Alnus glutinosa*, wet meadows and extensive forests dominated by Scots pine *Pinus sylvestris*. The urbanised areas of Lubrza village are located nearby.

In late April and early May, we collected shells on land and in the shallows of the watercourse. The material was analysed based on the methods used in the study of muskrat predation on mussels (Zahner-Meike and Hanson 2001). We identified each specimen to species or, in the case of major damage, to genus level using the identification key for mussels (Piechocki and Dyduch-Falniowska 1993). We determined the number of individuals of each species by adding the number of complete shells, which we considered as shells with both halves or one half with a hinge of both halves. In addition, we considered the highest number of left or right shell halves with a single hinge as individuals. Shell fragments and halves without a hinge were not considered.

We measured the length of 362 undamaged mussel shells. Most shells were severely damaged by the predator, so it was impossible to measure the entire length. The shell length was measured to the nearest mm using callipers. We assigned thin-shelled species of the genus *Anodonta* to the genus due to the high degree of shell damage. Smaller specimens with softer shells were too damaged to be measured. We analysed the thick-shelled species of the genus *Unio* separately for each species

To assess the differences in the number of mussels consumed between thin-shelled (*Anodonta*) and thick-shelled (*Unio*) species, we used a chi-square test of independence. This test was used to compare the observed quantities with the quantities that would be expected under the null hypothesis that raccoons feed equally on mussels of both genera. In addition, a one-way analysis

Figure 1. Location of the study area on the Paklica River in western Poland **A** a natural river section connected to an extensive wetland and a lake **B** a river section with reinforced banks running under a motorway.

of variance (ANOVA) was performed to assess the differences in shell length between species of the genus Unio. This method was chosen to determine whether the mean mussel lengths differed significantly between species groups. If significant differences were found, Tukey's HSD post hoc test was used to determine which pairs of species differed significantly. This analysis allowed us to test whether raccoons prefer mussels of a certain size. We used the significance level $p = 0.05$ for the statistical tests. The statistical analyses were performed with R version 4.3.1 (RStudio Team 2021).

Results

In the winter of 2020/21, raccoons consumed 2,340 mussel specimens belonging to five species in the studied section of the watercourse (Table 1). Thin-shelled species of the genus *Anodonta* and *Pseudanodonta* made up the

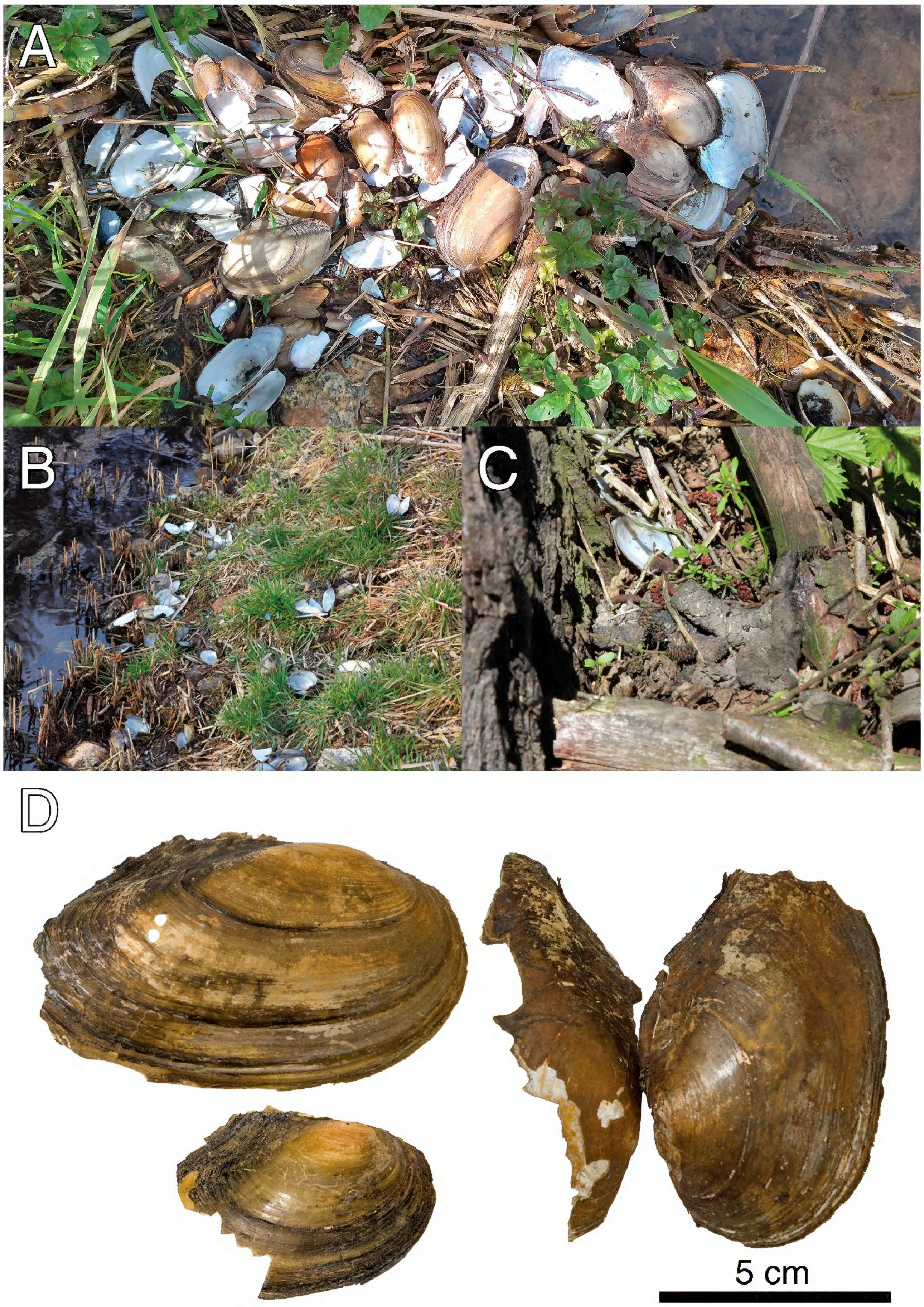

Figure 2. The signs of predation by the raccoon *Procyon lotor* on mussels Bivalvia **A B** accumulation of shells on the river bank **C** raccoon faeces at the feeding site **D** raccoon-specific shell damage.

majority of the material analysed (62%). The thick-shelled species of the genus *Unio* accounted for 38% of the identified specimens. The differences in the number of mussels foraged by raccoons of both genera were statistically significant (χ^2 = 140.8, df = 1, p < 0.001). The most common species on the raccoons' prey were the swan mussel *Anodonta cygnea* and the duck mussel *Anodonta anatina*. The mussels preyed on by the raccoons differed statistically significantly in size ($F_{2, 358}$ = 241.4, p < 0.001). The Tukey multiple comparisons of means test shows that the specimens of the genus *Anodonta* differ in their mean length from *Unio pictorum* and *Unio tumidus* (Table 2, Fig. 3).

Table 1. Mussels Bivalvia foraged by a raccoon *Procyon lotor* in the winter of 2020/21 in western Poland.

Species	Number of specimens N	Frequence %
Swan mussel *Anodonta cygnea*	909	38.85
Duck mussel *Anodonta anatina*	420	17.95
Painter's mussel *Unio pictorum*	408	17.44
Swollen river mussel *Unio tumidus*	367	15.68
Anodonta spp.	118	5.04
Unio spp.	108	4.62
Depressed river mussel *Pseudanodonta complanata*	10	0.43
Total	2340	100

Table 2. Comparison of the mean length of mussels Bivalvia foraged by raccoons *Procyon lotor* in the winter of 2020/21 in western Poland.

Comparison	Difference	P
Unio pictorum vs *Anodonta* spp.	-18.570	**0.000**
Unio tumidus vs *Anodonta* spp.	-17.271	**0.000**
Unio tumidus vs *Unio pictorum*	1.298	0.556

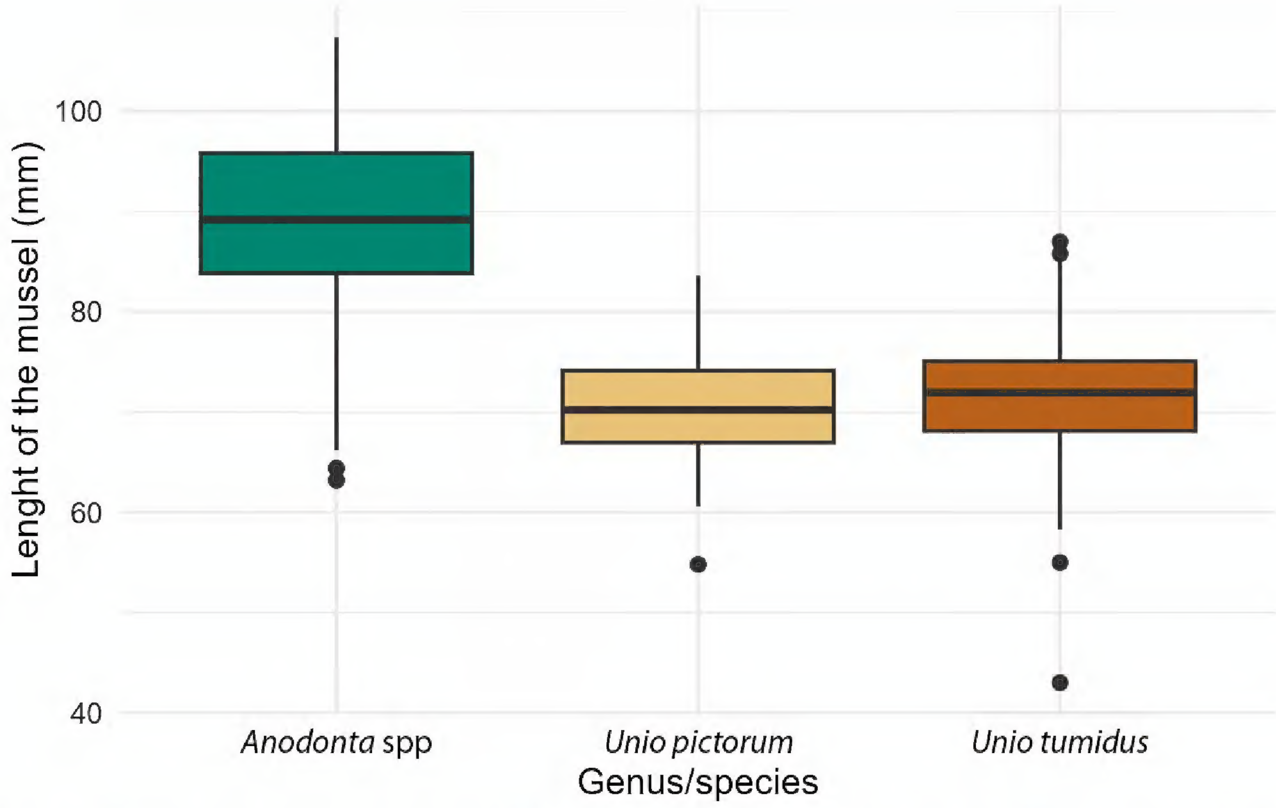

Figure 3. Shell lengths in mussels Bivalvia predated by raccoons *Procyon lotor* in the winter of 2020/21 in western Poland (*Anodonta* spp. N = 200, *Unio tumidus* N = 62, *Unio pictorum* N = 100).

Discussion

The results of our study show for the first time that the raccoon is a predator that can use mussels as an important food source in newly colonised areas in winter. In the raccoon's natural range, mussels can be an important part of the raccoon's diet under favourable environmental conditions, e.g. in coastal or lake areas (Smith et al. 1987; Simmons et al. 2014). Raccoons forage for mussels in shallow sections of watercourses where they are more easily accessible. In such cases, raccoons can prey on mussels on a large scale (Gagnon et al. 2004).

In our study, thin-shelled mussels predominated among the raccoons' prey. However, we do not know what preferences the raccoons have in this respect, as we did not analyse the species and age structure in the unionid communities prior to the study. This aspect would need to be analysed in more detail in further studies. Raccoons selectively choose larger bivalve specimens (Simmons et al. 2014). They are more likely to select thin-shelled species by destroying the shell at the posterior edge of the mantle (Gagnon et al. 2004). In our study, the most common prey of raccoons is the swan mussel, the largest native mussel species in Poland with an average length of 12.5 cm, reaching a maximum of 26 cm in rare cases (Piechocki and Dyduch-Falniowska 1993). Other species recorded in our study are somewhat smaller, but also belong to the group of bivalves with considerable body sizes (average shell length: swan mussel - 7.8 cm; painter's mussel - 7 cm; swollen river mussel 5.8 cm; depressed river mussel - 6 cm) (Piechocki and Dyduch-Falniowska 1993).

In the natural range of the raccoon, it was observed that the proportion of mussels in the raccoon's diet increased in winter (Rulison et al. 2012). In areas where the species has been introduced during the food-critical winter months, mussels can be valuable prey for raccoons. Foraging bivalves from cold water is associated with a significant loss of energy for the predator. Nevertheless, mussels are a high-calorie food that can provide a significant advantage in balancing the body's energy needs (Simmons et al. 2014).

In the literature, predation by raccoons on crustaceans, especially on endangered species, is considered to be an important threat (Ikeda et al. 2004; Boncompagni et al. 2021; Tricarico et al. 2021). Meanwhile, two of the five mussel species that are on the diet of raccoons in western Poland are threatened with extinction in Europe and their populations are declining. In the IUCN Red List, the swan mussel and the duck mussel have the status VU (Varnulable) for the area of Europe (Lopes-Lima and Prié 2024; Lopes-Lima et al. 2024a) and the depressed river mussel has the EN (Endangered) status (Lopes-Lima et al. 2024b). In the Polish Red Data Book of Animals - Invertebrates, both species have the higher threat status of EN (Zając 2004a, Zając 2004b). Three of the designated species: swan mussel, duck mussel and depressed river mussel are partially protected under Polish law (Dz.U 2022). The swan mussel is mainly found in oxbow lakes and eutrophic parts of lakes and is becoming increasingly rare in Poland due to the strong pressure of human activities. The duck mussel is the most resistant to changes in environmental conditions and is most numerous in bivalvian communities. The depressed river mussel occurs in Poland in small isolated populations, mainly in shallow and clear rivers (Piechocki and Dyduch-Falniowska 1993). At the same time, knowledge about the distribution of mussel populations is incomplete, resulting in the swan mussel and the duck mussel not yet having been reported from the area of our study.

Twenty years ago, when the Polish Red Data Book of Animals - Invertebrates was compiled, predation by invasive species was not considered a threatening factor for mussel populations. Nowadays, it seems that it should be considered as one of the most important threats and even surpasses some reported before, such as harvesting for amateur breeding. Further research could shed light on which other mussel species are foraged by raccoons and to what extent they utilise invasive mussel species found in Poland's inland waters in addition to native species.

Conclusions

The plasticity of adaptation to local food resources means that raccoons can utilise them intensively. Our observations suggest that in Central Europe mussels can be such a food source in winter. It can be assumed that they are one of the most important food sources in areas close to rivers or lakes when access to insects, snails, amphibians, birds, plant food and other components available during the growing season is insufficient. To determine the actual impact of an invasive opportunistic species such as the raccoon, an extensive field study focused on annual changes in prey communities is needed. Nevertheless, local observations such as ours show that the impact of the raccoon on native ecosystems should be considered more broadly, as this species has the potential to negatively affect also the populations of non-obvious and underreported prey species, such as endangered mussel species in our case.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

Conceptualisation: AW, JC. Data collection and analysis: AW, JC, BG, MC. Statistical analysis: JB. Visualisation: MC, AW, JC, JB. Writing: original draft: AW, JC, MC, BG. Writing - review and editing: AW, MC. All authors contributed to the final version of the manuscript and approved the submitted version.

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Data availability

All of the data that support the findings of this study are available in the main text.

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